

Results from an Extremely Sensitive Rayleigh-Scatter Lidar

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Abstract-Rayleigh-Scatter lidar systems effectively use remote sensing techniques to continuously measure atmospheric regions, such as the mesosphere (45-100km) where in situ measurements are rarely possible. The Rayleigh lidar located at the Atmospheric Lidar Observatory (ALO) on the Utah State campus is currently undergoing upgrades to make it the most sensitive of its kind. Here, the important components of these upgrades and how they will effect the study of a particular atmospheric phenomena, atmospheric gravity waves, will be discussed. We will also summarize what has been done to the system during this year to bring us to the threshold of initial operations.

I. INTRODUCTION

The Rayleigh-Scatter lidar system at the Atmospheric Lidar Observatory (ALO) at Utah State University is currently going through a series of upgrades to make it the most sensitive instrument of its kind. The previous version of the Rayleigh lidar operated for more than a decade on the USU campus and was successfully used to measure relative densities and absolute temperatures in the mesospheric region of the atmosphere (45-90 km). From these measurements, 11 years worth of temperature data were collected that allowed researchers to study structures and trends in the temperatures over a long time frame. Also, atmospheric phenomena such as atmospheric gravity waves (AGWs), planetary waves, and noctilucent clouds were studied.

After these upgrades to the system, it will be the most sensitive Rayleigh-scatter lidar in the world. Increasing the system's laser power and collecting area achieve this. The altitude range will also have been greatly expanded by increasing the number of PMT detection channels.

With the improved system, atmospheric phenomena, such as AGWs, which can travel throughout all altitudes of the Earth's atmosphere and can have small temporal and spatial variations, can be better studied. There is still much that is unknown about AGW creation at low altitudes and the dynamics of AGW propagation horizontally and vertically throughout the atmosphere. It will be an

excellent instrument for making AGW observations to determine their behavior and relate it to theory.

II. BACKGROUND

The term Rayleigh scatter refers to a particular type of scattering interaction between light and particles. In this case, the size of the particles is much smaller than the wavelength of the light. Another important aspect of Rayleigh scatter is that the wavelengths of the incident and scattered light are the same, or in other words the interaction between the light and scattering particle is elastic.¹ For example, Rayleigh lidar systems use incident laser pulses to induce Rayleigh scatter off of N₂ and O₂ molecules in the atmosphere and return light of the same wavelength, in our case 532 nm. This is much longer than the size of N₂ and O₂ molecules, which are both on the order of 0.1 nm in size. Rayleigh scatter dominates over other types of scattering above approximately 25 km (35 km after a major volcanic eruption such as Mt Pinatubo). The interpretation of the return signal is most straightforward below 100 km, where the major constituents are turbulently mixed.

In lower regions, different types of particles are added to the atmospheric mixture. These particles, such as aerosols (dust), are much bigger than N₂ and O₂ molecules. Incident light interacting with these particles results in a different type of scattering called Mie scatter. Mie scatter is characterized by scatterers that have sizes either on the order of or much larger than the wavelength of incident light.¹ Their scattering cross sections are much bigger than those for Rayleigh scatter, with the result that the signal from Mie scattering is much bigger at altitudes where Mie dominates over Rayleigh scattering.

A third type of scattering interaction differs from the previous two significantly. Raman scatter involves an inelastic interaction between the incident light and scattering particle; in other words, the incident and scattered wavelengths of light are no longer the same.¹ The wavelength of the scattered light depends on the type of scatterer and the wavelength of the incident light. For example, the Rayleigh lidar will transmit pulses at 532 nm. When it scatters from N₂, Raman scatter will lead to photons at 607 nm. The cross section for Raman scatter is the order of 10³ smaller than for Rayleigh scatter. As a

result the signal is small enough that it would only be detectable with the upgraded system below about 40 km.

Since lidar systems measure, specifically, the time of flight of a light pulse in order to determine the altitude or distance from the source to a scatterer, pulsed lasers are an essential component to their functionality. To detect the backscattered light, lidars first use large-mirror telescopes to capture the returned photons and then direct them into photon detectors that convert the physical, returned photons into a digital signal. The ALO Rayleigh lidar uses photomultiplier tubes (PMTs) for its detectors. After being directed onto the PMTs by the receiver optics, the photoelectrons from the photocathode cascade through the PMTs creating electronic pulses that are counted as a function of time (distance) by a multichannel-scaler (MCS). They are then downloaded to a PC, where they can be recorded and analyzed.

Each lidar is comprised of slight variations on this basic setup. The previous version of the ALO Rayleigh lidar, in particular, used as its transmitter one Spectra Physics Nd:YAG laser frequency doubled to emit a 532 nm pulsed beam that had a average power rating of 18-W or 24-W depending on the stage in its history. Its receiver was made up of one 44-cm collecting mirror and one PMT channel.² The previous system is depicted schematically in Figure 2. The large power output allowed measurements to be made high into the mesosphere to about 90 km while the dynamic range of the single detection channel limited the lower altitude to 45 km. The upgrades aim to increase the power output, receiving area and number of detection channels in order to increase the overall altitude range and sensitivity of the instrument.

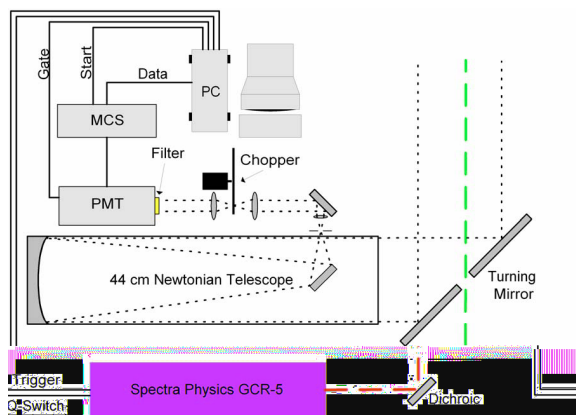


Figure 2. Previous Rayleigh lidar system that operated at the Atmospheric Lidar Observatory on the USU campus for 11 years (Herron 2004)

III. RAYLEIGH LIDAR UPGRADES

Through a series of instrumentation upgrades, the ALO Rayleigh lidar will become the Rayleigh-Mie-Raman (RMR) lidar. It will observe an overall altitude range of 15-120 km, spanning the stratosphere, mesosphere and into the lower thermosphere. It will also have improved temporal and spatial resolutions in its data collecting, which becomes important when atmospheric phenomena that have small variations over space and time are being studied.²

The first major upgrades to the system were made to increase the output power and the backscattered photon collection area. To do so, the group set up two Spectra Physics GCR series lasers in parallel to operate as one outgoing laser beam³ and constructed a large four-mirror telescope that has a combined receiving area of 4.9 m².⁴ A photograph of the four-barrel telescope is shown in Fig. 3 while an overall schematic of the new system is shown in Fig. 4.

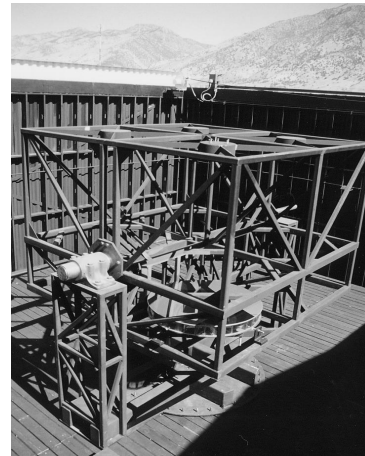


Figure 3. The four-barrel telescope that gives the ALO RMR lidar its 4.9 m² collecting area (Wickwar et al., 2001)

The power output and collecting area are multiplied to form the lidar figure of merit, called the Power-Aperture Product (PAP). With two lasers at 18 W and 24 W and a total collecting area of 5 m², the RMR lidar has a PAP value of 206 Wm². Since this figure of merit is commonly used as a measure of the sensitivity of a given lidar system, the RMR lidar's large PAP value makes it the most sensitive of its kind. In comparison, the previous system's PAP value was either 2.7 Wm² or 3.7 Wm² depending on which laser was being used.

With a significantly increased PAP value, the ALO RMR lidar will be able to obtain usable data from as high as 120 km in altitude. Unfortunately, by raising this upper limit, the lower limit of the lidar's altitude

range will also be raised from 45 km, previously, to 65 km. In order to bring the lower limit back down to the original lower limit of 45 km, a second PMT detection channel will be added that will span an altitude range of 40-90 km. To bring the lower limit down even further, a third channel measuring from 15-65 km and a fourth channel, equipped for Raman rather than Rayleigh scattering, measuring from 15-40 km will be added.

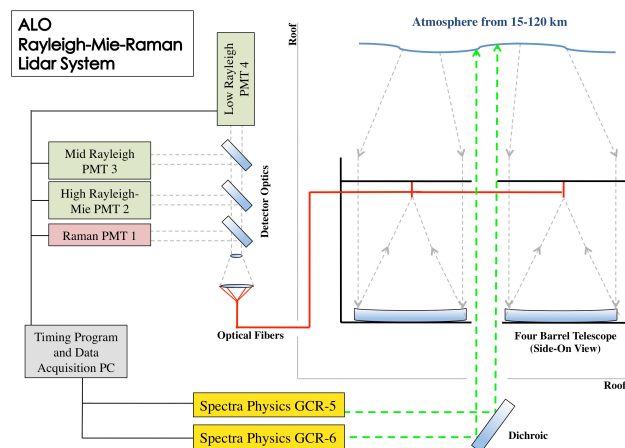


Figure 4. Schematic diagram of the new RMR lidar at ALO

Extending the upper and lower altitude limits will allow the ALO RMR lidar to cover the entire stratosphere, mesosphere and the lower thermosphere. Altitude ranges of these regions can be seen in Fig. 5. The amount and size of particles that are found in each of these regions tends to increase as altitude decreases. For this reason, the Mid and Low Detection channels must account for other types of scattering besides Rayleigh scattering.

The mid-altitude channel (15-65 km) will have to account for Mie scattering as well as Rayleigh scattering in its data analysis. Mie scattering differs from Rayleigh in that it comes from scatterers of sizes comparable to or larger than the wavelength of the incident light. The most prevalent examples of such particles are dust and aerosol particles, which are usually on the order of several microns, or one to two orders of magnitude larger than the 532 nm laser pulses.

Table 1. Altitude ranges and types of scattering detected by each of the four PMT channels

PMT Detection Channel	Type of Scattering	Altitude Range
Raman	Raman, Rayleigh, Mie	15-40 km
Low Rayleigh-Mie	Rayleigh, Mie	15-65 km
Mid Rayleigh	Rayleigh	45-90 km
High Rayleigh	Rayleigh	65-120 km

For the lowest altitude channel, Raman scattering will be observed rather than Rayleigh or Mie. Raman scattering differs greatly from the first two types because it involves inelastic scattering between the incident light and particle scatterer. In Raman scattering, the incident light excites the atom or molecule up a level from the ground state as before, however, when the photon is re-emitted, it is of a different frequency than the incident photon. For this reason, the Raman scatter detection channel must be designed to accept a different wavelength of light than the incident photons that are sent out at 532 nm.

The most prevalent atmospheric constituents between 15-40 km are N_2 molecules and they interact with 532 nm incident light in this way. The resulting photons from this interaction have a wavelength of approximately 607 nm. Thus, the receiving optics to the PMT detector must allow for 607 nm wavelengths and block any other wavelengths. The data analysis software will need to be modified to include the Klett inversion algorithm, which will combine the data from the 532 nm and 607 nm channels.

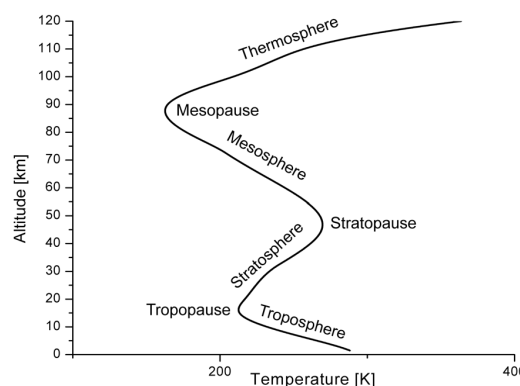


Figure 5. Graph of the various atmospheric regions, which are defined by the temperature reversals as altitude is increased. (Herron 2004)

By increasing the altitude range that the lidar is able to observe, more comprehensive studies of the atmosphere and the dynamics of the coupling between regions will be possible. Derived temperatures from direct observations of variation in density over altitude can be added and compared to the 11 years worth of temperature data that was taken by the previous system. Also, the increased sensitivity of the instrument will allow for either smaller spatial or temporal resolutions in the data integration. This will effectively give a researcher the means to “zoom in” on interesting phenomena that must be understood on smaller altitude or time scales. Examples of such phenomena, which were initially detected by the old system, include: noctilucent clouds, anomalous thin layers and AGWs. Due to their overall importance to

the dynamics of the atmosphere and omnipresent nature, AGWs will be focused on in the following section.

IV. IMPLICATIONS ON AGW DETECTION

Atmospheric gravity waves are oscillations of air parcels, which are lifted by a buoyant force and restored to their initial positions by gravity.⁵ The importance of atmospheric gravity waves can be summarized as such,

“[AGWs] have been a subject of intense research activity in recent years because of their myriad effects and their major contributions to atmospheric circulation, structure, and variability. Apart from occasionally strong lower-atmospheric effects, the major wave influences occur in the middle atmosphere, between ~10 and 110 km altitudes because of decreasing density and increasing wave amplitudes with altitude.”⁶

As stated, AGWs have the strongest effects on the middle part of the atmosphere. For this reason, much is to be learned from their observed properties and dynamics throughout the mesosphere in particular. Instruments that focus on this area, like the previous ALO Rayleigh lidar, have been able to make observations of these waves by monitoring density and temperature fluctuations.

AGWs arise from many different types of sources, though they most commonly originate from storm convection in the upper troposphere (~15 km); orography, or wind over mountains, (~0-5km); and wind shears, for example, near the edge of the polar and subtropical jet streams (~7-12 km or 10-16 km). The latter of these two sources may be significant to the ALO RMR group because the lidar is situated on the USU campus in Cache Valley that is surrounded by two prominent Rocky Mountain ranges, the Bear River and Wellsville ranges. Due to this distinct location, the ALO RMR lidar will have ample opportunity to study the dynamics of AGWs shortly after they have left their topographic sources at around 3 km. The upgrades to the system will make this possible by extending the observable range down to ~15 km. With the previously described extended altitude range, the RMR system will be able to monitor the various forms of AGW propagation throughout the stratosphere, mesosphere and into the lower thermosphere; precisely where major wave influences occur.⁶

Being able to observe AGWs on smaller spatial and temporal scales will bring insight into many of the effects of and on AGWs about which relatively little is known. Remote sensing techniques have been able to provide more understanding of gravity wave scales, amplitudes, fluxes, and spectra and have addressed instability dynamics, vertical

propagation, variations with altitude, and seasonal and geographic variability.⁶ As an extremely sensitive remote sensing instrument, the RMR lidar intends to continue and improve upon these areas of interest.

As an example, AGWs studies using the previous ALO Rayleigh lidar were conducted and reported in Durga Kafle's dissertation, *Rayleigh Lidar Observations of Mesospheric Gravity Wave Activity Above Logan, Utah*. In his dissertation, Kafle depicts gravity wave activity through graphs of altitude vs. density perturbation profiles as is shown in Fig. 6.

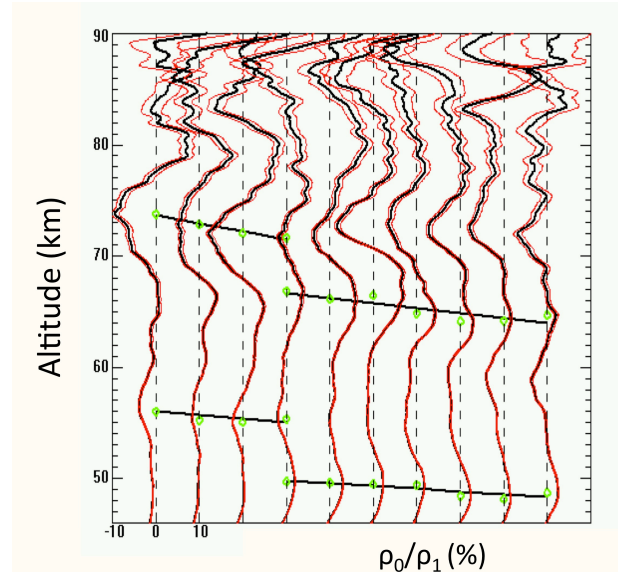


Figure 6. Profiles of relative density perturbations at one-hour intervals caused by AGWs for Feb. 25, 1999 (Kafle 2009)

The value of the horizontal axis comes from the equation

$$\rho(z) = \rho_0(z) + \rho_1(z) \quad (2)$$

where $\rho(z)$ is an individual measured density profile, $\rho_0(z)$ is the background mean state of the atmosphere and $\rho_1(z)$ is the wave induced perturbation density.⁶ Thus, in Fig. 6 the ρ_0/ρ_1 values show the relative density perturbations with respect to altitude.

The straight lines that traverse the green dots in the figure show phase velocities and the vertical wavelength. The vertical wavelength value is the difference between successive maxima or minima. As can be seen in this particular graph, gravity waves of approximately 17 km in vertical wavelength with a downward phase velocity of about 0.4 m/s were observed that night.⁵

This is a typical wavelength for the gravity wave spectra found by Kafle using the ALO Rayleigh lidar. The work done by Kafle was limited by the Rayleigh system's spatial integration resolution of 3

km for profiles taken in the maximum altitude range of 45-90 km. This meant that all of the waves found had on the order of 12-17 km vertical wavelengths and about 0.2-0.5 m/s phase velocities. Using the vertical wavelengths and phase velocities allowed one to calculate the distance the wave had traveled from its source. Many of the waves found in Kafle's work had sources around 2000 km away from the ALO site.

With the new RMR lidar system, researchers will be able to make similar observations with finer altitude resolutions. The altitude resolution in Fig. 6 is 3 km and were integrated over an hour's worth of photon collecting and the entire 45-90 km range of the system. Work by Slansky in 2009 showed waves of much smaller vertical wavelengths using 600 m instead 3 km resolutions but were limited to the 45-60 km altitude region.⁷ The RMR system will be able to reduce these integration limits to roughly about 37.5 m and 1 hour, or 3 km and 1 minute over the entire 15-120 km altitude range. This means that one can adjust either the time resolution or the spatial resolution to be much finer. The spatial and temporal resolutions can also be adjusted simultaneously to achieve greater sensitivity, however these resolutions will in turn be somewhat larger than 37.5 m and 1 minute.

Whichever smaller resolution is chosen depends on what aspect of a certain atmospheric phenomena is being carefully studied. For instance, the Rayleigh system was unable to detect AGWs with smaller vertical wavelengths than 3 km whereas the RMR lidar will be able to detect waves a vertical wavelengths 37.5 m and greater. Similarly, the old system could not measure AGWs with periods shorter than about an hour and the new system will be able to measure well below that temporal constraint.

IV. STATUS OF THE ALO RMR LIDAR

Gravity wave observations are a major aspect of the science that has pushed the ALO Rayleigh group to greatly improve the system. With that in mind, a great deal of progress has been made in the past year in accomplishing the aforementioned upgrades to the system.

Beginning last spring, I joined the Rayleigh group as a PhD candidate. At this point, a big push to get the system up and running was put into place. First, the two Spectra Physics GCR series lasers were arranged in parallel so that their individual beams could be combined on a turning mirror and were aligned as one outgoing beam.

Once this transmitted laser beams were oriented vertically, we transitioned to aligning the

four large mirrors, which act as the returned photon collectors, parallel to the laser beams. The method of aligning the mirror was somewhat involved but over the course of several nights became streamlined and was well documented for future mirror alignments.

A great deal of the existing equipment had to be reevaluated and sometimes modified to be included as part of the new system. Much of this work involved the existing PMTs and their power supplies and housing units. Two custom dynode chains were designed and inserted into sockets that attached to two separate tubes, themselves. From there, the PMTs were placed in Peltier cooler housings, which were cooled using an Affinity chiller.

From there, various tests were conducted to learn more about the PMTs' performance. The voltages from high voltage power supplies were optimized to maximize the signal-to-noise ratio (SNR) for both PMTs. Tests were also designed and conducted to test the linearity of the PMTs responses to increasing light on the photocathode.

We then began to work on combing the returned signals from all four mirrors into a beam and then sending that beam into multiple PMT channels. This proved to be a more challenging optical engineering feat than originally expected, yet we were able to come up with a new design that used optical technology loosely based of that used in submarine periscopes to achieve our goal.

We are currently ready to send one beam of combined signal from the four mirrors into the High Rayleigh PMT channel. This will allow us to verify our upper altitude range limit of approximately 120 km and will give us more insight into what the lower limit will be as it is expected to rise with the upper limit and be at about 65 km.

From there, it will be straightforward to add the Mid Rayleigh and Low Rayleigh-Mie channels this summer. The existing IDL software package will also have to be edited, at that time, to account for the multiple detection channels. The Raman channel will follow shortly after the other three channels but could take more time to get up and running as it involves different optical components and major changes to the data analysis software.

V. CONCLUSION

In summary, the upgrades to the Rayleigh-Mie-Raman scatter lidar are coming to a close. Significant progress has been made in the design and construction of the instrument and it will soon be ready to take measurements from altitudes between 65-120 km. From there, more detector channels will

be added, allowing for a total altitude range of 15-120 km. The much greater sensitivity of the instrument can also be used to obtain finer spatial and/or temporal resolutions in the data analysis. These upgrades will be essential to continue and expand the study of atmospheric gravity waves as they propagate above Logan, Utah.

VI. ACKNOWLEDGEMENTS

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